Damage Tolerance of Integral Structure in Rotorcraft

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Summary

The rotorcraft industry has rapidly implemented integral structures into aircraft to benefit from the weight and cost advantages over traditionally riveted structure. The cost to manufacture an integral structure, where the entire component is machined from a single plate of material, is about one-fifth that of a riveted structure. Furthermore, the integral structure can weigh only one-half that of a riveted structure through optimal design of stiffening structure and part reduction. Finally, inspection and repair of damage in the field can be less costly than riveted structure. There are no rivet heads to inspect under, reducing inspection time, and damage can be removed or patched readily without altering the primary structure, reducing replacement or repair costs. In this paper, the authors will investigate the damage tolerance implications of fielding an integral structure manufactured from thick plate aluminum.

Introduction

The 7050 aluminum alloy is being used by the rotorcraft industry for integral structure because of excellent strength to weight/cost ratios and because procurement/manufacture-to-shape is a straightforward process. Integral structure holds the promise of significantly reducing the overall cost of ownership for any built-up structure. For instance, a fuselage skin with integral frames and stringers can be machined from a single thick plate of aluminum. Traditionally, a fuselage skin is manufactured from thin aluminum plate with mechanically fastened (riveted) frames and stringers. The assembly time of a built-up panel can be nearly an order of magnitude more than an integral structure machined using computer-controlled systems. Moreover, the inspection and repair of an integral panel can be significantly less than a built-up structure. The reduction in part count simplifies inspections, and repair can be achieved using bonded patches without modification to the existing structure.

However, manufacturing a structure from a single plate of material, instead of assembling several components manufactured from different materials, can leave the designer with less than optimal material properties. For instance, a fuselage skin in a riveted panel is oriented in such a way that the optimal material properties are utilized. Conversely, an integral structure is machined from a thick plate and may be loaded such that all of the material orientations are significant, including the less than optimal orientations. Mechanical testing of thick plate aluminum [1, 2] has exhibited anomalous behavior compared to thin plate material [3]. Most significant has been the material response in the short-transverse (S-T) orientation [4]. This material orientation is not in the primary load path in riveted structure and was therefore never seriously investigated. However, in an integrally stiffened structure the S-T material orientation can be in the primary load path. In this paper, the authors will present damage tolerance data for 7050 aluminum in the long- (L-T) and short-transverse (S-T) material orientations and comment on anomalous behavior that was observed. Finally, the authors demonstrate the effect of transitioning from thin to thick plate could have on the damage tolerance of a rotorcraft integral structure.

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Damage tolerance information

Integral structures are loaded multiaxially, promoting fatigue crack propagation in all of the material orientations. However, little research has been done to quantify the effect of loading aluminum alloys in each orientation. Fatigue crack growth data was obtained for both thin [3] and thick [1, 2] plate 7050 aluminum. Fatigue crack growth data is used in a damage tolerance assessment to predict the time to failure for a structure subjected to cyclic loads. Testing of a thin plate was performed in the L-T material orientation, commonly used for the primary load path in riveted structure, and is presented in Figure 1. Examination of the data reveals trends that can effect the damage tolerance of a rotorcraft structure. The crack growth rate (*da/dN*) increases as the stress ratio, *R*, increases at the same stress intensity range, ΔK. This phenomenon is common in most aluminum alloy data reported in the literature and implies an improved resistance to crack growth with lower stress ratios. Further, as the stress ratio drops, the fatigue crack growth threshold and cyclic fracture toughness increase. The threshold is used in a damage tolerant design as the point where a fatigue crack will not propagate, typically defined as a crack growth rate approaching 10^{-10} meters/cycle. This concept is similar to the endurance limit used in a fatigue (stress-life) design. The cyclic fracture toughness is used to determine when a part will fail, usually defined as the point where the crack growth rate exceeds 10^{-4} meters/cycle. The data set presented in Figure 1 does not contain information at either of these crack growth rates. However, extrapolation of the data is commonly performed when making a damage tolerance assessment and can be used in making general observations.

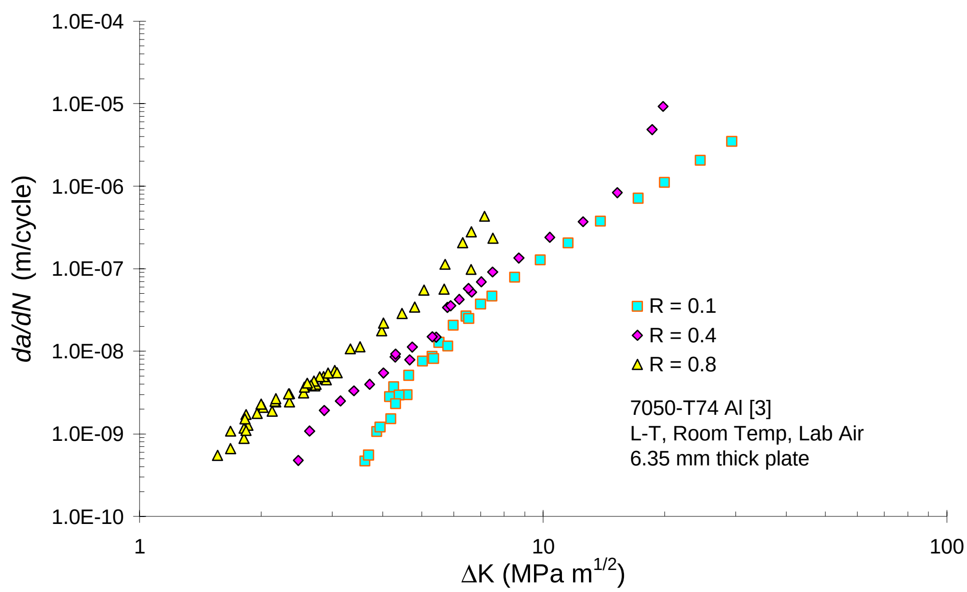

Figure 1: Fatigue crack growth rate data for 7050-T74 aluminum thin plate [3].

The fatigue crack growth rate data for 7050 aluminum thick plate is presented in Figure 2. Testing was conducted in both the L-T and S-T material orientations. The data presented for this material does not exhibit the shift with respect to stress ratio like the thin plate. The independence of stress ratio on the fatigue crack growth rate is difficult to explain without additional testing. The use of this data implies that a structure subjected to a high stress ratio loading would propagate a crack at a slower rate than would a structure made from a thin plate. However, the cyclic fracture toughness of the thin and thick plate materials in the L-T orientation looks nearly identical. The improvement in the fatigue crack growth rate behavior, and consistent fracture toughness between thick and thin materials, could lead to the conclusion that a structure manufactured from a thick plate is better for a damage tolerant application. Unfortunately, the S-T orientation of the thick plate appears to have a 50% reduction in cyclic fracture toughness at a low stress ratio when compared to the L-T orientation. This reduction in toughness could have a dramatic effect on the usable life of an integral structure that has a load path in the S-T orientation. However, the fatigue crack growth threshold for the R=0.5 S-T data has similar threshold behavior to the thin plate R = 0.4 L-T data. This could imply that the low crack growth rate of the thick plate is similar to the thin plate irregardless of orientation.

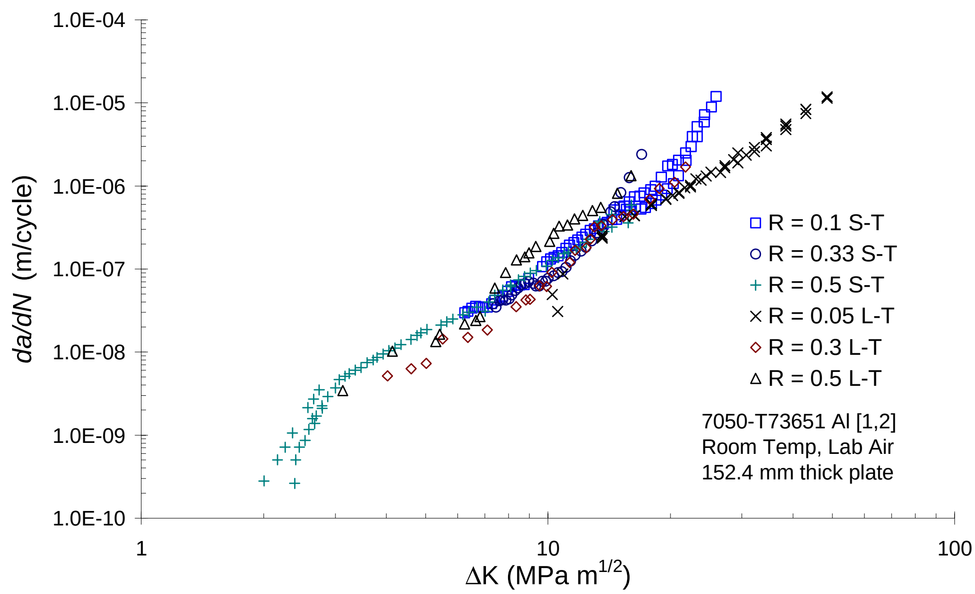

Figure 2: Fatigue crack growth rate data for 7050-T73651 aluminum thick plate [1, 2].

Integral structure

For this study the authors have chosen to investigate a curved integrally stiffened panel as depicted in Figure 3. The dimensions presented in this figure are in U.S. customary units and the panel is depicted as flat because the schematic was taken directly from the reference [5]. The panel was cycled at a maximum stress of 103 MPa with a stress ratio of 0.1 and a frequency of 2 Hz. This translates to an initial stress intensity range of 49 MPa $m^{1/2}$. The central stiffener of the panel was severed with an EDM notch and fatigue precracked to a length of 178 millimeters. Optical measurements were taken during the test at each crack tip on both the front and back faces of the specimen. The integral panel was machined such that the primary loading was perpendicular to the T orientation (*i.e.* the load-line was along the L orientation). Further, the design of the stiffeners promotes fatigue crack growth in the S-T orientation. The fatigue crack growth data are plotted in Figure 4 as the change in crack length from the precrack to failure for the average (front-back) of each tip. Figure 4 also shows the position of the stiffeners. The rapid acceleration of the crack through the integral stiffener is not uncommon for this type of structure [6]. However, the lower fracture toughness of the 7050 aluminum alloy in the S-T orientation, as compared to the L-T, may have further accelerated the failure of the panel.

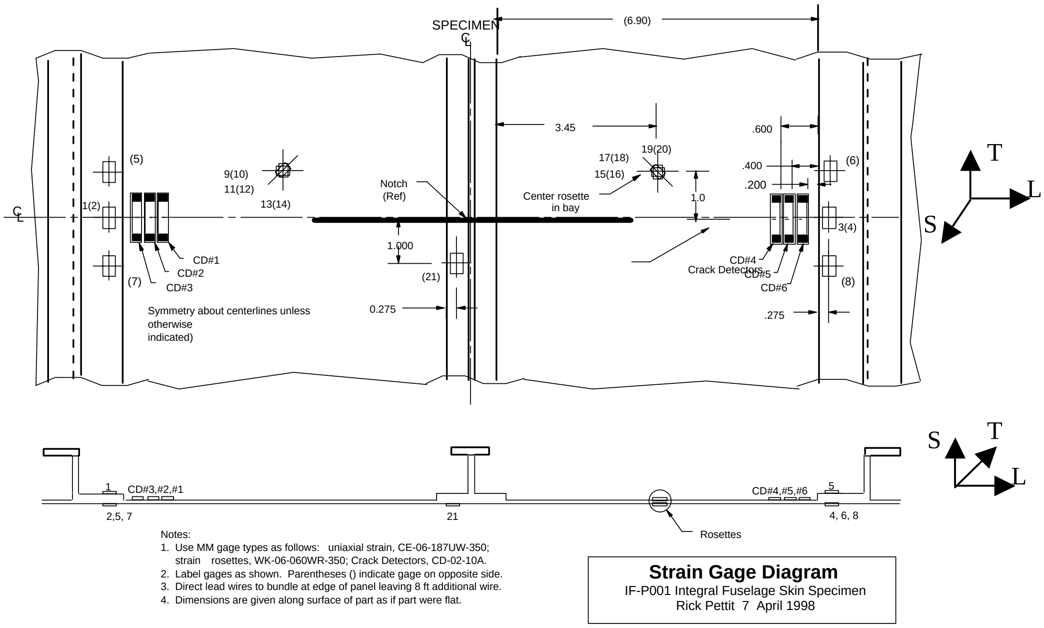

Figure 3: Schematic of an integrally stiffened panel.

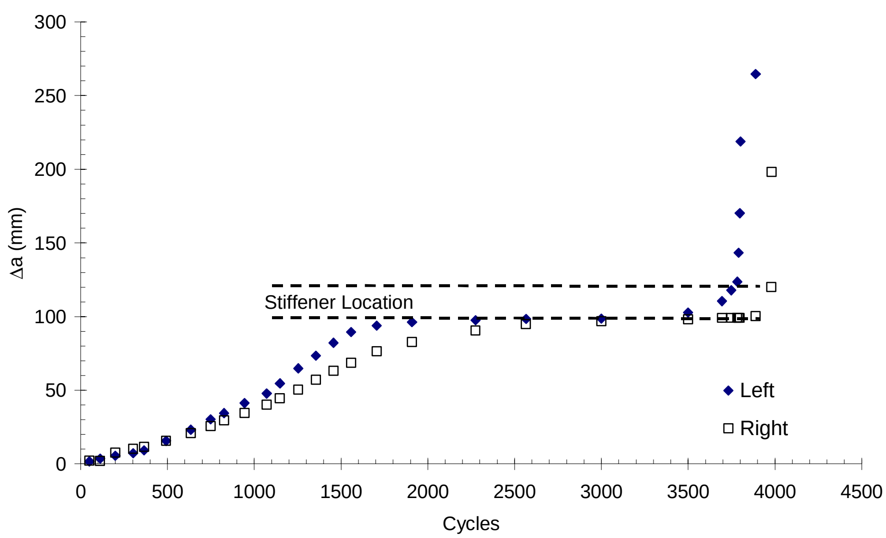

Figure 4: Crack length versus cycles for an integrally stiffened panel.

Evaluation of material orientation

A simulation of the integral panel test was performed using the NASGRO computer code [7]. The panel was modeled as a flat panel (no panel curvature or stiffeners) with the same cross-sectional stress levels and initial flaw size as the integral panel test. Therefore, a direct comparison is not possible, but general trends may be observed at comparable load levels. The analyses were performed using both thin and thick plate 7050 aluminum data presented herein, with the thick plate using the L-T and S-T orientations. The predicted cycles to failure are shown in Figure 6. The initial stress intensity range was approximately 49 MPa $m^{1/2}$, similar to the integral panel. Based on these analyses, the thick plate appears to have better damage tolerance than the thin plate, when comparing the L-T orientations. However, examining the data for the thick plate aluminum, 49 MPa $m^{1/2}$ is very close to the cyclic fracture toughness of the S-T orientation. Therefore, the analysis performed using the S-T orientation data has significantly higher initial growth rates and fractured almost immediately.

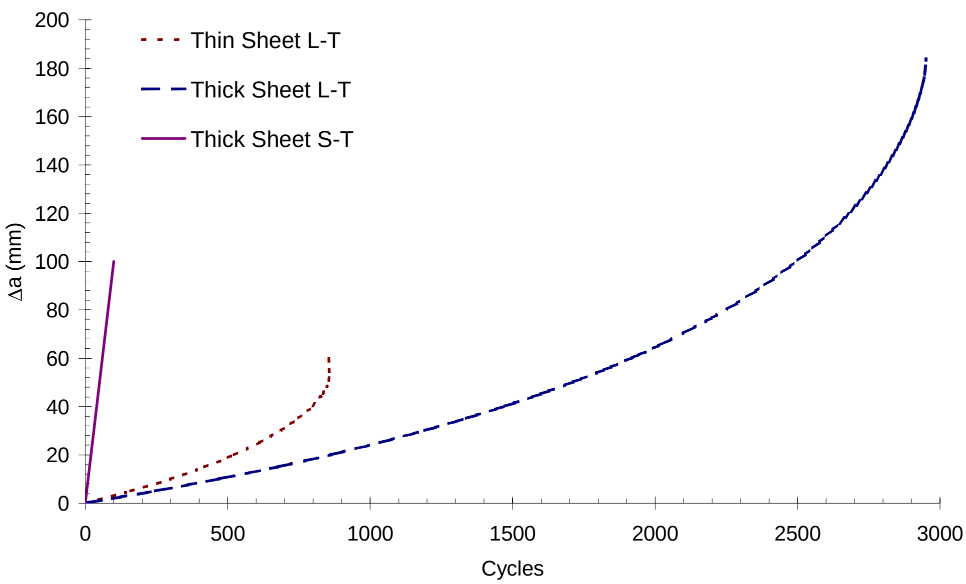

Figure 6: NASGRO predicted crack length versus cycles for a center-cracked panel.

Summary

Thick plate 7050 aluminum has excellent fatigue crack growth properties in the long-transverse material orientation when evaluated against comparable materials. This fact has driven the rotorcraft industry to adopt this alloy for use in integral structure. These structures are machined from thick plates and loaded in service multi-axially. Little study has been done on alternate material orientations, such as the short-transverse, that are now in the critical load path. The generation of fatigue crack growth data in the short-transverse orientation has shown an anomalous trend. The fatigue crack growth behavior of the thick plate 7050 does not exhibit a dependence on stress ratio like most aluminum alloys. Further, the cyclic fracture toughness of the S-T orientation is about one-half that of the L-T orientation.

The damage tolerance assessment of the integral panel highlights the need for understanding the complete material response of an alloy before fielding a component. Most material testing is performed in the long-transverse direction because this orientation has been in the primary load path of riveted structure. With the transition to integrally-stiffened structure, and with multi-axial loads, the failure of a structure in the short-transverse direction is a possibility. Assuming the data presented herein is representative of a thick plate of 7050 aluminum, an order of magnitude or more degradation of damage tolerance life is a possibility. This does not portray integral structure in a beneficial light. However, if the designer of the structure is aware of this behavior prior to fielding a component, the probability of failing a structure in the short-transverse direction can be minimized.

Finally, additional coupon-level and structural testing must be done to quantify the anomalous behavior of thick plate 7050 aluminum and verify the safety of the aircraft using this material.

Acknowledgement

The authors would like to thank Marcia Domack of NASA Langley Research Center and William Johnston of Lockheed Martin for the integral panel test data. A comprehensive report of this testing will be published in the future.

Reference

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